

An Adaptation to an Existing Facility of the E921 Precision Measurement of the Decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and Other Rare and Precision Measurements in K^+ and π^+ Decays.

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E921 Collaboration *

Abstract

Fermilab experiment 921, originally known as CKM, has, after scientific approval by Fermilab, been nationally reviewed by the P5 committee with the following recommendation:

“... CKM was found to be an elegant world class quark flavor physics experiment. It could not, however, be recommended for construction given presently foreseen funding constraints.”

We outline here a redesign and adaptation of the CKM technique from the proposed new separated Kaon beam facility to an unseparated beam experiment that can be mounted in the existing KTeV facility. The overall sensitivity goal of the primary measurement remains 100 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal events with a small background. This sensitivity is achieved by exploiting both low-background regions available in the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay. The E921 physics program consists of the primary measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay amplitude to a precision limited by theoretical uncertainties and a suite of rare and precision studies in both K^+ and π^+ decays. The π^+ decay physics is an new opportunity made possible by the large pion flux in the unseparated beam.

The major new technical challenge is tracking a 230MHz unseparated positive beam with an upstream magnetic spectrometer at $\times 5$ the rate planned for in CKM. Ultra high rate tracking chambers based on Micromegas technology, which have been recently developed and demonstrated in the NA48/2 experiment at CERN, make this a tractable problem. The savings by using an existing beam-line and experimental facility will reduce costs by a factor of $\times(3 - 4)$ relative to the cost associated with the new CKM facility.

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1 Introduction

The major physics goal of E921 is the theoretically cleanest determination of $|V_{td}|$ by making a low background measurement of the branching ratio of the ultra-rare charge kaon decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with statistical precision approaching 10%. This measurement provides one of the most sensitive tests for physics beyond the Standard Model by testing if the flavor physics of the kaon system is consistent with the same Standard Model parameters seen in the b meson systems. This remains one of the most important unachieved measurements in high-energy physics. We are presently the only experiment in the world undertaking this challenge. Our approach has been rigorously reviewed and approved by numerous expert technical panels, the Fermilab PAC, and Directorate. In the end, the national P5 review, which can't identify sufficient funds for us to mount the experiment, characterizes CKM as an “*elegant world class quark flavor physics experiment*”.

We are unwilling to abandon a world class piece of physics which we, and Fermilab, are uniquely positioned to undertake and achieve. The confluence of this financial impasse and recent demonstrations in very high rate tracking detector technology have presented us with the opportunity to adapt our original technique to a more cost effective solution. We can exploit, to much greater degree, existing facilities and equipment; thus substantially reducing the additional resources required to successfully make this measurement.

The nature and status of our original design was summarized for the DOE Facilities Panel Review in February 2003 [1]. This document will well serve the reader as a succinct primer and reminder of the original CKM plans. Complete details are available in our proposal [2] and on our web-site [3].

We summarize here a redesign of CKM for a $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ experiment in an unseparated beam utilizing the existing KTeV beam line and experimental hall at Fermilab. For definiteness we will call this design E921. The original, approved, Fermilab E921 experiment with a separated 22GeV/c kaon beam in the MP beam line and MP9 detector hall will be called CKM here.

In summary, it appears feasible with this approach to achieve the same physics goal as in CKM: a measurement of the branching ratio of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with a statistical uncertainty and background fraction both approaching 10%. There are significant advantages in the E921 design relative to CKM: in particular the photon veto requirement are much easier to achieve and therefore cheaper. Tracking ~ 20 pions and protons nearly in-time with each beam kaon is a formidable challenge but the strategy developed here appears feasible, subject to detailed background simulations now underway.

Our primary physics goal is a determination of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay amplitude to a precision limited by theoretical uncertainties. The large pion flux in the unseparated beam adds to the additional measurements in K^+ decay, which we have enumerated in our proposal, an expanded range of additional rare and precision measurements in π^+ decay.

The recent establishment of direct CP violation in the neutral kaon system ($Re(\epsilon'/\epsilon)$) was based on high energy kaon beam experiments which are now excellent candidates for evolution to the E921 design. The SCRF beam separation system central to the CKM design required a relatively low energy beam and detector design. Relaxing this constraint, at the cost of handling a beam with 4% kaons rather than 60%, makes the E921 design feasible in the KTeV experiment as well as the NA48 beam and apparatus at CERN. Adaptations similar in character to those developed here for the KTeV beam line and detector would be required for that beam and apparatus.

2 Physics Motivation and Reach

2.1 Physics Goals

2.1.1 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

We require an experiment designed to measure the branching ratio of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with physics sensitivity comparable to the original CKM experiment with a separated beam: ~ 100 signal events for a branching ratio of 1×10^{-10} with $< \sim 10\%$ background acquired with 2–3 years of data taking. The motivation for a $\sim 5 - 6\%$ statistical uncertainty in the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay amplitude is to match the theoretical uncertainty, estimated at $\sim 8\%$, in this amplitude due to uncertainty in the mass of the charmed quark.

New work since the CKM proposal to expand the phase space of the search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ allows us to include both low-background regions; PNN1 as before and a PNN2 region between $K^+ \rightarrow \pi^+ \pi^0$ and the onset of three body decays. This provides an additional observable not contained in the original CKM proposal. The ratio of the number of signal events observed in these two regions is a measure of the form-factor in the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay mode. The form-factor is predicted to be identical to that in $K^+ \rightarrow \pi^0 e^+ \nu_e$ decays. The precision achievable in this ratio would only be 25% in E921, but if the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio were twice the Standard Model predicted value (as presently observed with a large uncertainty by BNL e787/949) this ratio could be quite valuable in sorting out possible beyond-the-Standard-Model hypotheses. Now that we understand that backgrounds can be controlled in “Region II”, as we called PNN2 in the proposal, this ratio is equally measurable with the CKM technique, where we would have twice the statistics of E921.

2.1.2 Pion Decay Physics

Rare pion decays have played an important role in limiting anomalous scalar, pseudo-scalar, and tensor couplings through precision measurement of the helicity-suppressed $\pi^+ \rightarrow e^+ \nu_e$ and $\pi^+ \rightarrow e^+ \nu_e \gamma$ decays. The helicity suppression constrains the Standard Model branching fraction of $\pi^+ \rightarrow e^+ \nu_e$ to 1.2×10^{-4} , providing a window for amplitudes from virtual high mass exchanges arising from physics beyond the Standard Model to compete in the total branching fraction.

$$R_{\pi_{l2}} = \frac{\Gamma[\pi^+ \rightarrow e^+ \nu_e (\gamma)]}{\Gamma[\pi^+ \rightarrow \mu^+ \nu_\mu (\gamma)]} \quad (1)$$

The expected ratio of $R_{\pi_{l2}}$ (equation 1) can be calculated reliably to the extraordinary precision of 0.05% [4]. This robust Standard Model prediction enables precision measurement of R_π to probe contributions from sources such as lepto-quarks at $200 GeV$, lepto-quark compositeness at $1 TeV$, multiple Higgs models and TeV-scale Brane models. The ratio R_π is currently measured with a precision of 0.4%. This invites an experimental campaign to push this window by another factor of $\times 8$ to match the theoretical certainty.

New physics can be further probed by precision measurement of the $\pi^+ \rightarrow e^+ \nu_e \gamma$ form factor. For center of mass photon energies greater than $10 MeV$ the expected branching fraction is 5.5×10^{-7} [5]. The (V-A) based form factors of this decay are calculated to high precision which provides extraordinary sensitivity to new amplitudes. New physics preferentially distorts the high photon energy region of the Dalitz plot, where the dominant inner bremsstrahlung component is relatively small. The PiBeta experiment at PSI has recently reported precision measurements of a suite of rare pion decays [5,6] including $\pi^+ \rightarrow e^+ \nu_e \gamma$. PiBeta reports an intriguing departure from the expected (V-A) form factor of high statistical significance in the region of high photon energy [6]. This has

motivated the PiBeta collaboration to propose further running to study this anomaly, which has recently been approved by PSI. Hints of this anomaly has been seen in previous experiments [7].

The latest round of precision rare pion decay measurements have been performed using stopped pions [8, 9]. The stopped-pion measurement uncertainties are now dominated by background and detector acceptance modeling estimations [5, 6, 8, 9]. The experiments have made careful estimates of these systematic errors based on a demonstrated understanding of detector performance. Nevertheless, further progress requires a technique with reduced or at least different systematic uncertainties which motivates consideration of an in-flight decay experiment. The large fraction of pions in the high intensity E921 unseparated beam presents an opportunity to probe in-flight pion decays with unprecedented sensitivity. Stopped pion techniques by necessity are complicated by the presence of stopping material and measurement of low energy photons and electrons. In contrast, pion decays in the E921 apparatus occur in vacuum and produce high energy ($\sim 10\text{GeV}$) decay electrons and photons that can be measured with very high precision with modern fully active calorimeters. The high flux of E921 pions permits matching the statistical precision of previous pion decay measurements with three months of modest intensity Main Injector beam. The detector systems required for these measurements are a subset of the full complement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ instrumentation motivating consideration of a program of world-class pion decay measurements prior to full $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ running with the E921 apparatus.

2.1.3 Other Kaon Decay Physics

In the CKM proposal [2, 10, 11] we demonstrated that the large kaon flux and excellent properties of the CKM spectrometer gave access to many rare kaon decays, with sensitivities approaching 10^{-12} in parallel with the main $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ program. The CKM apparatus included two high precision velocity (RICH) and magnetic spectrometers for both the incident kaon and charged decay products, a forward photon calorimeter and a muon detector, hermetic photon and muon veto coverage to suppress background processes, and a powerful trigger and DAQ system. The capability for precise measurement and identification of decay particles together with the suppression of background processes are quite important to kaon decay studies.

The general thrust of additional measurements are motivated by the search for new physical processes beyond the Standard Model. These include:

- Lepton flavor violation in kaon decays.
- New scalar, pseudo-scalar or tensor weak interactions in decays like:
 $K^+ \rightarrow e^+ \nu_e$, $K^+ \rightarrow \pi^0 l \nu_l$, and $K^+ \rightarrow \pi^+ l^+ l^-$
- T-odd correlations in $K^+ \rightarrow \pi^0 l^+ \nu_l \gamma$ decays.
- New low-mass particles in kaon decay like $K^+ \rightarrow \pi^+ S^0$, and $K^+ \rightarrow \pi^+ \pi^0 P^0$ (Goldstino)

There are also precision studies of low energy hadron physics in weak decays like:

- Radiative decays.
- $\pi\pi$ interactions in $K^+ \rightarrow \pi\pi l^+ \nu_l$ decays.
- Form-factor studies.

These hadronic studies are important for further developments of lattice QCD, chiral perturbation theory, other hadronic models and quark confinement in general.

All of these studies remain feasible in the E921 design with an unseparated beam. The details of these measurement are changed with the new geometric and kinematic conditions. These are being re-evaluated with the E921 design. A disadvantage of E921 is the reduction of 60% in the number of kaon decays studied with respect to CKM. This will reduce the statistical sensitivities of all measurements by this factor. At the same time however the kinematics in E921 will greatly improve the measurement of π^0 's in kaon decays with the CsI calorimeter. The E921 kinematics and calorimeter performance can in many cases compensate the reduced kaon flux; for example, in decays like $K^+ \rightarrow \pi^0 l^+ \nu_l \gamma$. For processes like $K^+ \rightarrow \pi^- \mu^+ \mu^+$ where sensitivity is dependent on background suppression rather than total decay flux, the E921 environment will not degrade the sensitivity expected in CKM.

As discussed previously, the E921 experiment has sensitivity for new interactions that may be present in $\pi^+ \rightarrow e^+ \nu_e$ and $\pi^+ \rightarrow e^+ \nu_e \gamma$ decays. The analogous measurements in the kaon system are also sensitive probes of physics beyond the Standard Model. The E921 experiment affords simultaneous measurements for both $R_{\pi l_2}$ and $R_{K l_2}$ (equation 2).

$$R_{K l_2} = \frac{\Gamma[K^+ \rightarrow e^+ \nu_e (\gamma)]}{\Gamma[K^+ \rightarrow \mu^+ \nu_\mu (\gamma)]} \quad (2)$$

These complementary studies can exploit the excellent environment of the E921 apparatus to reduce the associated systematic uncertainties. These measurements have significant sensitivity for new types of interactions. For example, as was shown in [12,13], the measurement of $R_{K l_2}$ provides a precision test of $\mu - e$ universality, which can probe lepto-quark models up to $\Lambda_{LQ} > 150 TeV$.

2.2 Cost Goals

A new requirement, in order to make this measurement feasible in the US, is to achieve this measurement at a substantially lower cost than the 101M\$ cost assigned to CKM.

A re-estimation of the cost for CKM with maximum utilization of existing beam lines and enclosures at Fermilab and including the results of our test beam studies of photon veto and other prototypes has been made. Notable among the detector cost reductions is the vacuum veto sub-system, where the now-measured high energy inefficiency [14] allows the CKM veto requirements to be met with 1/2 the veto detector volume, corresponding to about a 50% reduction in sub-system cost. The re-estimated total CKM cost is in the 50 – 55M\$ range in this model.

The largest cost subsystem remaining in the CKM design, after the changes above, is the separated kaon beam. These costs includes the SCRF separator cavities, RF power supply, super-fluid liquid Helium cryogenics plant, civil construction required for the beam-line and cryo-plant, etc.. These costs total 15 – 20M\$ of the revised CKM cost estimate above.

An unseparated beam experiment in an existing area and beam-line can, by further subtraction, be achievable for less than 40M\$. This figure is a “top-down” upper bound achieved by removing all items from the CKM cost estimate not required for E921. An initial “bottoms-up” estimate of the cost of the E921 detector, based on scaling the full CKM costs for revised beam-line elements, detector components and channel counts, is $\sim 25M\$$.

All total costs discussed here are in standard US HEP FY2001 accounting units. These include all labor costs, contingency (typically 50%), G&A (overhead), etc. For scale, these costs are typically $\times 2.5$ the cost of materials and services alone.

3 Adaptation to an Unseparated Beam

3.1 Ideas behind this adaptation

If the beam momentum constraints of the separation system are removed, then a decay-in-flight experiment like CKM can be scaled in beam momentum by lengthening the apparatus by a momentum scale factor. Apertures, coverage, decay fractions, etc. all scale correctly. What does not scale in the CKM design are the velocity spectrometers (the K^+ and π^+ Riches) which are tuned to particular particle velocities ($\beta\gamma = P/M$). CKM is designed to accept decay π^+ 's in the forward hemisphere in the K^+ rest frame. At a higher beam momentum there is a more backward region of π^+ in the K^+ rest frame where the π^+ in the lab still fall in the same lab velocity region for the same pion RICH as designed for CKM. These π^+ 's have somewhat larger lab angles than in CKM making vertex resolution better and getting the π^+ 's further from the beam.

The increased beam momentum allows for significant improvements in the performance of the photon vetoes systems. The minimum lab angle of both the accepted π^+ 's and the corresponding photons from K_π^2 decays on the other side of the beam from the π^+ has increased. This minimizes the photon inefficiency due to an overlap of the charged pion and a photon at the photon veto. The minimum energy π^0 will increase as minimum K^+ beam momentum exceeds the maximum π^+ momentum usable in the RICH. The photons from these high energy π^0 's will preferentially hit the CsI rather than the VVS photon vetoes. The CsI has even lower inefficiencies for high energy photons ($> 1\text{GeV}$) than the conservative limit of 1×10^{-5} for lead-scintillator VVS modules which we have adopted based on our test-beam results on a prototype at Jlab where we observed 3×10^{-6} for electrons incident on the face of a module [14]. Both the increased photon energy scale and the decreased inefficiency for the highest energy photon provide important opportunities to increase the photon energy threshold.

The most obvious potential limitation of an unseparated beam is the presence in the Upstream Magnetic Spectrometer (UMS) of more than $20\times$ the K^+ flux of other charged particles in the beam. In such an experiment with a 10MHz K^+ flux, the UMS will have to track $\sim 230\text{MHz}$ of charged particles. The kaon fraction of the unseparated beam is now a limiting factor.

The underlying ideas for this adaptation are to double the kaon beam momentum and increase the momentum bite while maintaining a small parallel beam. The pion RICH has usable momentum resolution ($\Delta p/p < 2\%$) for pion momenta up to $30\text{GeV}/c$. With a secondary beam of $37 - 53\text{GeV}/c$ produced in a solid angle of $1 \times 1\text{mrad}^2 = 1\mu\text{sr}$ we have a minimum π^0 energy of 7GeV and a beam size in the decay volume of $(1 \times 1\text{cm}^2)$. The signal π^+ 's are in the angular range $4 - 14\text{mrad}$ allowing a vacuum beam pipe for the un-decayed beam through the detector without acceptance loss.

The “pencil” kaon beam is an important asset. The position resolution given by size of the beam in the decay volume is comparable to the position resolution of the UMS system extrapolated to the decay point. Requiring that decay daughter tracks come from the beam is an additional constraint against miss-measurements and scatters in upstream material.

3.2 Beam

With the choice of an unseparated $37 - 53\text{GeV}/c$ positive beam with a $1\mu\text{sr}$ solid angle produced by $120\text{GeV}/c$ protons on a 1 interaction length (40cm) Be target, the fluxes of particles entering a decay volume 86m downstream of the production target are shown in table 1.

The choice of positive secondary beam is based on the production cross-sections for $120\text{GeV}/c$ protons on a Be target. In this secondary momentum range the kaon fraction is about 4% for either charge beam while the production cross-section for K^+ is about $5\times$ larger than for K^- . Therefore

$120\text{GeV}/c$ protons/sec		4×10^{12}
secondary momentum		$37 - 53\text{GeV}/c$
secondary transmission		50%
decay volume fluxes	protons	130MHz
	π^+	100MHz
	K^+	10MHz
	total	230MHz

Table 1: Decay volume secondary particle fluxes

it takes considerably less 120GeV proton flux to product the necessary kaons. In a negative beam the non-kaon component is all π^- which would have $2/3$ as many interactions in the material of the upstream detectors. Negative beam remains a option at the cost of 1×10^{13} protons/sec on target, or more likely, a somewhat larger solid angle secondary beam. With the choice of positive beam the requirements for Main Injector protons to drive E921 are similar to those for CKM.

The secondary beam is achromatic (no net bend) in the decay volume. This is a requirement of both the geometry of the NM2-4 enclosures and the need for a small parallel beam. The goal for the beam size is $1 \times 1\text{cm}^2$ in the decay volume with small $\sim 0.1\text{mrad}$ angular divergence. The upstream kaon decays in this beam amount to 23% which are accounted for in Table 1. Pion decays are at $1.4\times$ the rate of kaon decays.

This beam design is motivated by the existing NA48/2 charged beam whose characteristics are similar. There is an on-going effort to develop a detailed beam-line design for the NM2 enclosure. This design appears to meet all the requirements. Critical details of collimation and beam tails are currently under study.

3.3 Detector

This section describes the proposed changes to the CKM detector to accomplish E921. In general terms the changes are small changes to the RICHes, DMS and veto systems. The UMS and the whole issue of kaon tracking and momentum spectrometer redundancy for the kaon measurements are significantly different.

3.3.1 Layout

The E921 layout is shown in Figure 1. The coordinate system has its origin at the kaon production target (the KTeV coordinate system) and the detector elements are arranged to fit into the KTeV beam enclosure (NM2) and the KTeV detector hall (NM3-4). The region between these two enclosures is a 30cm (12in) beam pipe through a large, buried, pile of steel muon absorber. This region is shown in Figure 1 as the section of vacuum decay volume from $66 - 84\text{m}$. For comparison the CKM layout is shown in Figure 2 at the same scales as in Figure 1 directly above.

The only significant difference in the back end of these layouts is the vacuum beam pipe to allow the unseparated beam to exit without additional interactions in the E921 design. The decay volume is scaled in length and the density of photon vetoes is reduced by another factor of two due to the much reduced requirements for detection of low energy photons discussed in more detail below. The Kaon RICH is largely the same: the radiator gas is changed to Hydrogen at 1.1atm and lengthen by 20%. The large changes to the detector are the upstream magnetic spectrometer

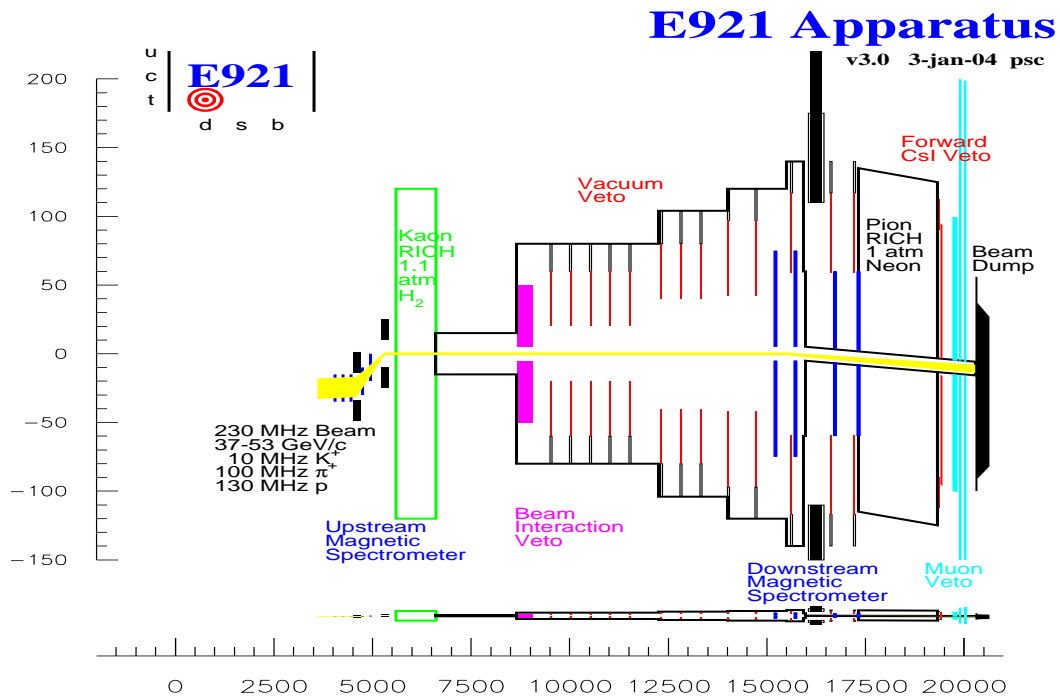


Figure 1: overall plan view layout for the E921 design.

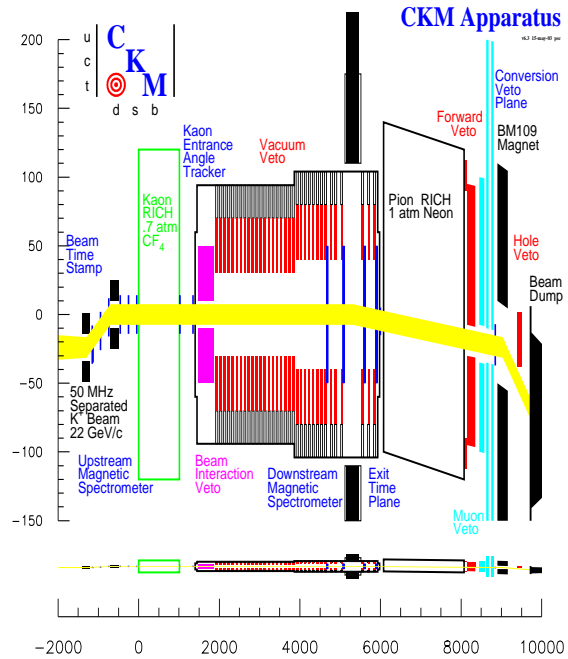


Figure 2: overall plan view layout for the CKM design.

chambers and the unseparated beam itself.

3.3.2 Kaon RICH

The Kaon RICH now needs to measure the velocity of beam kaons from $37 - 53 GeV/c$. The working gas of choice is Hydrogen at $\sim 1.1 atm$. With a $12m$ long gas volume and a single $12m$ focal length mirror with a $2cm$ hole for the beam we should be able to achieve all the requirements while minimizing the amount of material traversed by the beam. The windows on the kaon rich can be small in diameter and very thin. Nonetheless, the material in the kaon RICH windows dominates the material seen by the beam. A critical issue is controlling the potential backgrounds from the interactions and multiple Coulomb scattering in this material. With the present design the total material traversed by the beam from the last station of UMS chambers through the Kaon RICH and into the decay volume vacuum amounts to 5×10^{-3} radiation lengths and 4×10^{-3} interaction lengths.

The lowest momentum kaons have a $5mrad$ Cherenkov angle so the light from the last $2m$ of gas goes in the mirror hole. Due to the large momentum bite of the beam the distribution of Cherenkov photons across the phototubes is much more uniform than in CKM. We estimate we would require about 300 PMTs for the kaons rings with an average rate of $300 KHz$ per tube.

Looking at the $100 MHz$ of beam pions is very difficult. All the pion light would hit one ring of ~ 100 PMTs with ~ 15 photons per pion for an average tube rate of $\sim 15 MHz$. Protons are below Cherenkov threshold and therefore unobservable in this counter. The Kaon RICH provide a precision spectrometer for only the kaons allowing us to measure well the velocity and time of only the 4% kaon component of the beam.

3.3.3 DMS

The straw-tube planes designed for CKM will meet the E921 requirements with little change. We will need to physically leave out straws that are within $5cm$ of the beam to leave room for the exiting beam pipe. There are no accepted pion to be tracked in this region so there is no acceptance loss. We will have to revisit the redundancy issue in the first DMS station where only 5 planes may not be sufficient with $10cm$ swathes missing in all views.

3.3.4 Pion RICH

The pion RICH design is largely the same as for CKM. It has useful resolution ($dP/P < 2\%$) in the momentum range $14 - 30 GeV/c$. There will now be the exiting vacuum beam pipe running down the middle of the radiator volume. We need to split the mirror, sending half the light up and the other half down to minimize the Cherenkov photon losses from the beam pipe obstruction. The loss from photons before they are reflected by the mirror is small; most π^+ 's are at larger angles than their Cherenkov angles in Neon.

3.3.5 Photon Veto Systems

The minimum π^0 energy in the E921 design is $37 - 30 = 7 GeV$. The roles of the VVS and FVS are now inverted relative to the CKM design: 90% of the photons from K_{π^2} hit the FVS (CsI) and only $\sim 10\%$ hit the VVS. In all cases at least one photon from the π^0 hits the plane of the CsI though a few are still in the beam hole.

We will rotate the CsI by $30mrad$ to eliminate any projective cracks (the largest photon angle at the CsI is $20mrad$) we can achieve a high energy ($> 1 GeV$) photon inefficiency of 3×10^{-6} : a value

consistent with the latest measurements made in Japan [15]. Since we require a π^0 inefficiency of $< 1.5 \times 10^{-7}$ this implies that we can tolerate an average inefficiency on the lower energy photon from K_π^2 of 5%!

The E921 VVS uses the 5 existing ring counters from KTeV, which have square holes, together with 3 large and 5 small VVS modules of the CKM design where the small modules now have 20cm radius holes rather than the 30cm radius planned for CKM. The reduced efficiency required for low energy photons will allow us to use 2mm thick lead plates, as are used in the existing modules from KTeV. This reduces the amount of scintillator and wavelength shifting fiber per module by a factor of two relative the CKM design.

We've simulated the π^0 inefficiency as we did for CKM. We set a threshold of 1.5MIP everywhere, including a 700MeV threshold in the CsI and remove the BM109 magnets and HVS accepting 100% inefficiency for photons in the beam hole. We can achieve a π^0 inefficiency of 1.0×10^{-7} , somewhat better than the values of 1.5×10^{-7} achieved in the CKM design. With a minimum threshold of 100MeV the electronics and rate challenges in the photon veto systems are much reduced. Questions regarding veto rates from thermal neutrons, which were raised in the CKM design, are now moot.

3.3.6 Muon Veto Systems

The muon veto systems (MVS) remains unchanged from the CKM design. This system incorporates the existing KTeV muon vetoes. With this addition the MVS is probably over-specified; its requirements will be reviewed.

3.3.7 UMS

The original MWPCs planned for CKM have little hope of handling 230MHz of unseparated beam. There is a region in the achromat where the charged particles are dispersed over an area $7 \times 2cm^2$ or $\sim 17MHz/cm^2$. The Saclay group has developed a new kind of detector to play the role of UMS chambers in NA48/2 experiment. "KABES" is a TPC-type detector using MICROMEGAS as an amplification gap. It has operated reliably in up to 20MHz of charged beam flux with beam spot sizes of $\sim 1cm^2$ [16]. These chambers drift ionization perpendicular to the beam axis so the appropriate scaling is by the width of the beam perpendicular to the drift direction; 7cm in our case. Direct scaling of the NA48/2 results would allow us to operate at 140MHz. We need to push this technology another factor of < 2 in rate to allow operation at 230MHz. These chambers put very little material in the beam; typically of order 10^{-3} radiation lengths per $\{x, y, t\}$ measurement station. Spatial and time resolutions of 100 μm and 0.8nsec respectively have been achieved in NA48/2.

In order to provide redundancy for a KABES-like UMS system, which might have trouble with multiple track reconstruction efficiency, we plan to use BIVS as an active collimator to veto beam track that scatter in the Kaon RICH gas or other upstream material. BIVS is 30m downstream of the kaon RICH. Assuming we make the BIVS hole 10cm in diameter, 10 \times the size of the beam, any charged track that scatters or produces charged or neutral secondaries at angles $> 1.7mrad$, will be vetoed by BIVS. The total interaction rate in the Kaon RICH is $\sim 1MHz$. While this would be a significant veto rate, it is 10 \times less than the 10MHz veto rate we planned from upstream muons in the CKM design.

With the small $1 \times 1cm^2$ beam in the decay volume the spatial resolution of an upstream tracking system extrapolated $\sim 100m$ from the measurement into the middle of the decay volume will be comparable to the position resolution given by the size of the beam there. The Kaon RICH also

does not (and did not) have sufficient angular resolution to usefully resolve the beam divergence. These two systems form a redundant pair of magnitude of momentum and magnitude of velocity measurements of the kaon. With KABES for the UMS chambers each should give a independent time measurement with resolution for a track or ring much better than $1nsec$.

A critical issue to resolve in E921 is to understand and demonstrate control of the potential backgrounds from the high flux of pions and protons in the unseparated beam. In the CKM design the only important interaction backgrounds were from K^+ interactions in upstream material and residual gas. These were estimated at < 4.0 and < 2.1 background events respectively. In the CKM background evaluations we included $7.5MHz$ of pions and protons and found no significant accidental backgrounds. We must re-evaluate the probabilities for an accidental overlap of a good non-decaying kaon and all combinations of interaction and miss-measurement of $30\times$ the flux of untagged pions and protons.

The first layer of our defense is BIVS which assures that any pion scatter large enough to get into the acceptance region with lab angle $> 4mrad$ can't come from a scatter in the Kaon RICH region without traversing BIVS. It takes a minimum of an accidental time coincidence with a kaon plus at least two other mishaps (scatter, interaction, mis-measurement) to generate a background. Without heroics we can probably achieve a resolution of the time difference of the pion and kaon RICH ring of $0.5nsec$. With a $\pm 2\sigma = 2nsec$ timing cut on this quantity and a beam particle every $4nsec$ half the kaons will be free of such accidental backgrounds. The out of time tails will measure all these accidental backgrounds. But, we need to know they are small enough.

3.3.8 Detector Systems Removed

The Beam Time Stamp (BTS), Kaon Entrance Angle Tracker(KEAT), Exit Time Plane (ETC) and Conversion Veto Plane (CVP) have all been removed simply because none of these scintillating fiber or wire chamber planes can handle the $\sim 230MHz/cm^2$ beam rate. Their functions are largely by covered by BIVS as an active hole veto in place of the KEAT and the lower kaon flux and higher photon veto thresholds of the E921 design.

The BM109 and Hole Veto System (HVS) were removed both to make the detector fit an NM3-4 and because we could afford to ignore the photons in the beam hole without compromising the overall π^0 inefficiency.

3.4 Acceptance

parameter	CKM	E921
$120GeV/cprotons/sec$	5×10^{12}	4×10^{12}
Kaon momentum	$22 - 23GeV/c$	$37 - 53GeV/c$
decay volume	$19 - 42m$	$90 - 150m$
K+ decay fraction	13%	16.5%
PNN1 acceptance	$\sim 1.9\%$	2.06%
PNN2 acceptance		6.62%
total	$\sim 1.9\%$	5.00%*

Table 2: Comparative acceptance estimates

We have simulated the E921 geometry as was originally done for the CKM. In Figure 3 are shown the distributions in K^+ and π^+ momentum, Z of the vertex and missing neutral mass-squared for

the basic sample defining cuts: $90 < Z_{vertex}(m) < 150$ and $14 < p_{\pi^+}(GeV/c) < 30$. Since the lowest momentum beam K^+ is $37 GeV/c$ there is an implicit cut on the momentum of the missing neutral state of $> 7 GeV/c$. The dependence of the production on K^+ momentum is included. The shaded regions of the missing neutral mass-squared plot show the definitions of PNN1 and PNN2 regions (Region-I and Region-II in the notation of the CKM proposal). These are cut $0.010(GeV/c)^2$ from the K_π^2 peak and below the onset of K_π^3 decays.

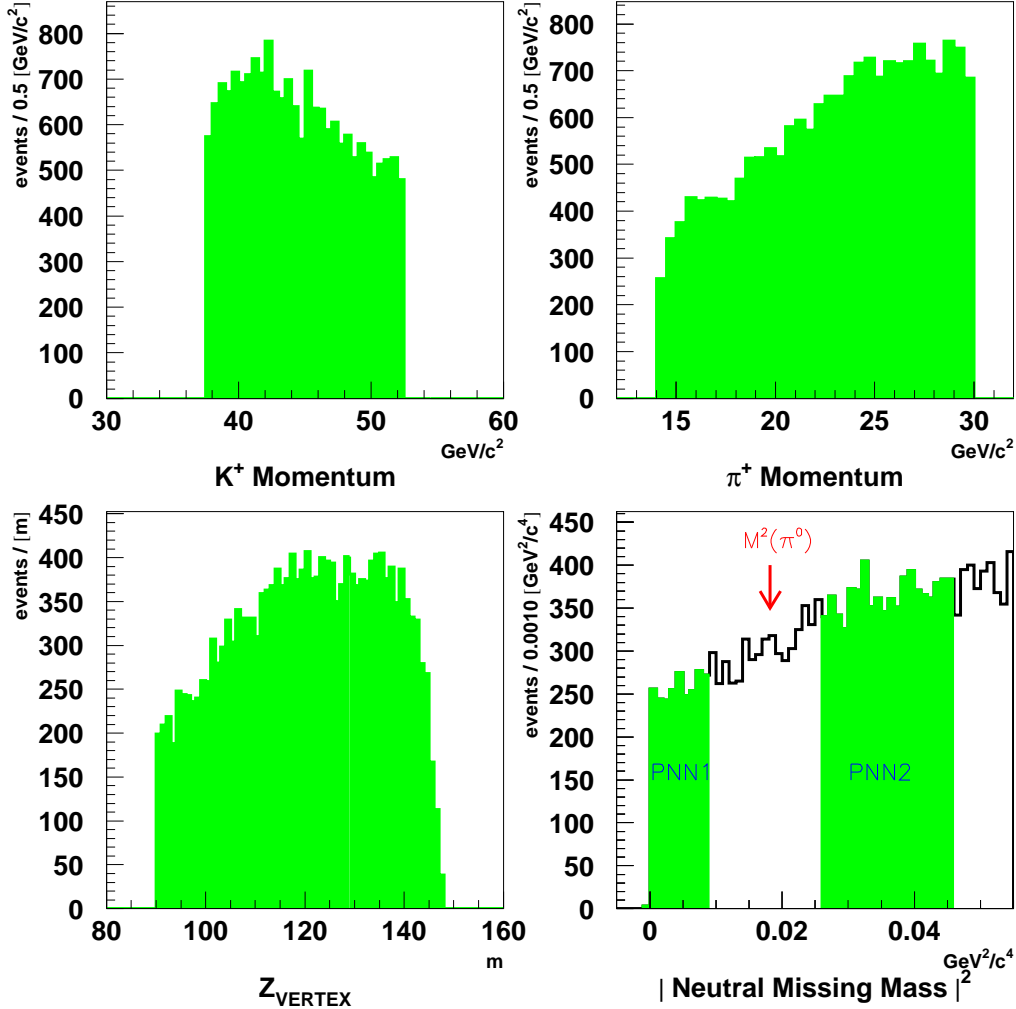


Figure 3: General acceptance properties for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal events. The lower right plot shows the missing-mass squared recoiling against the π^+ . The left and right shaded regions in this plot are the PNN1 and PNN2 signal regions, respectively.

The acceptances in the PNN1 and PNN2 neutral missing mass-squared regions are tabulated in Table 2. The PNN1 acceptance is 2.1%, a bit larger than the corresponding CKM acceptance of $\sim 1.9\%$. The PNN2 acceptance is quite large (6.6%). We have artificially limited this value in the sum in Table 2 and subsequently to a total PNN acceptance to 5% as a conservative estimate

since the initial background estimate in the region were and acceptance of $\sim 1 - 1.4$ times the PNN1 acceptance with 20 – 30% background.

Figure 4 shows the pion lab kinematics for the PNN1 and PNN2 regions as well as for K_π^2 . All accepted pions are in the angular range from 4 – 15 mrad.

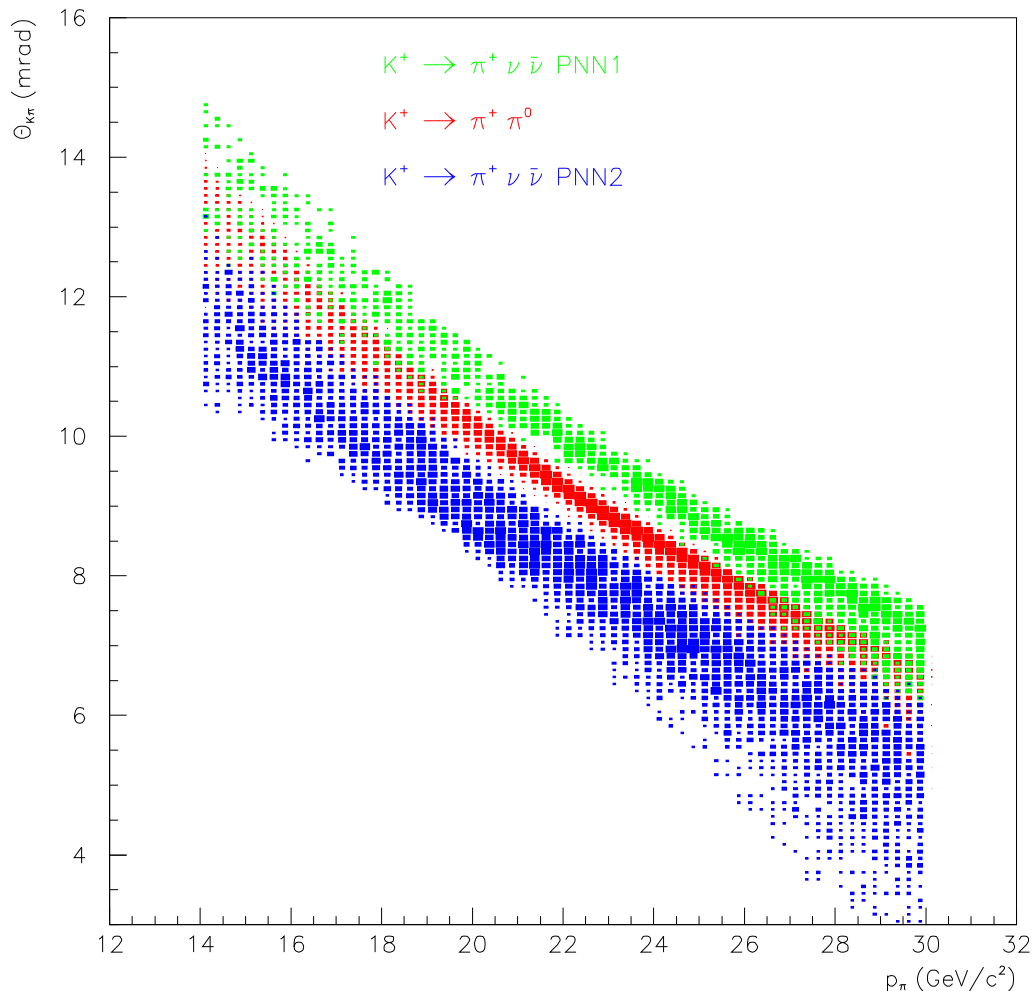


Figure 4: Pion lab kinematics for K_π^2 , PNN1 and PNN2.

4 Preliminary Background Estimates

We have reproduced in table 3, the background summary from the CKM proposal adding a column for our present understanding of how these backgrounds change in E921. These studies are neither complete nor final. An entry of TBD indicates that work is still in progress.

The negligible backgrounds remain so, save the case of an accidental overlap of a beam kaon with another beam track, which as noted above, might now become significant. Accidentals from

Background Source	CKM Proposal	E921
$K^+ \rightarrow \mu^+ \nu_\mu$	< 0.04	-
$K^+ \rightarrow \pi^+ \pi^0$	3.7	~ 5
$K^+ \rightarrow \mu^+ \nu_\mu \gamma$	< 0.09	-
$K^+ A \rightarrow K_L X$ followed by $K_L \rightarrow \pi^+ e^- \nu$	< 0.14	-
$K^+ A \rightarrow \pi^+ X$ in trackers	< 4.0	TBD
$K^+ A \rightarrow \pi^+ X$ in residual gas ($10^{-6} torr$)	< 2.1	TBD
Accidentals (2 K^+ decays)	0.51	0.17
Accidentals (K^+ + beam track)	-	TBD
Total	< 10.6	

Table 3: PNN1 Background estimates in terms of effective branching ratio ($\times 10^{-12}$).

two kaons drops with the kaons flux by a factor of 3. Presently the $K^+ \rightarrow \pi^+ \pi^0$ background has increased after the effects of reduced material in the beam, improved photon veto inefficiency and the removal of the KEAT are all taken into account. If necessary we can lower the photon veto energy thresholds somewhat to reduce this background contribution.

The interaction backgrounds in the trackers and residual gas have not yet been reevaluated. We expect these to go down. The cross section for a kaon of twice the CKM beam momentum to produce a pion plus at least $7 GeV$ of unobservable missing energy should be less than it was in CKM. The amount of material in the beam is also less in E921 than in CKM, however there is twice as much residual gas in the lengthened E921 decay volume.

5 E921 Physics reach

As shown in Table 2, by folding the accepted kaon momentum distribution from Figure 3(upper left) with a kaon decay probability we arrive at an average of 16.5% of the kaons decaying in the 60m long fiducial decay volume. This same fraction for the fiducial volume of the CKM design is 13%.

In Table 4 we have translated the acceptances into physics signal and background estimates. We have scaled the kaon fluxes for CKM and E921 by their respective decay fractions and the same running time. Applying the nominal 1×10^{-10} branching ratio and including another loss of 15%, to include dead-times and other losses we get the signals and background for each region tabulated. We haven't included PNN2 for CKM in the sums since we didn't propose it.

The additional background in the PNN2 region does not significantly alter the statistical precision on the measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio. To be compelling the E921 results must satisfy two criteria; demonstration of a clean signal and precision measurement of the branching ratio. We demonstrate a clean signal for the kinematically unconstrained $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay mode in the PNN1 region where the signal to noise ratio is designed to be better than 10/1. With this demonstrated we may add the events from second region, which has somewhat higher background, in order to improve that statistical precision on the branching ratio.

parameter	CKM	E921
$K^+ flux [MHz]$	30	10
beam-sec/year	0.75×10^7	0.75×10^7
years of data	2	2
sensitive K decays	5.8×10^{13}	2.5×10^{13}
nominal Branching ratio	1×10^{-10}	1×10^{-10}
taxes (other losses)	-15%	-15%
PNN1 (s+b)	$95+ \leq 10$	$44+ \leq 4$
PNN2	$(130+ \leq 40)$	$62+ \leq 20$
total	$95+ \leq 10$	$106+ \leq 24$
Br precision	$< 11\%$	$< 12\%$

Table 4: Comparative physics reach estimates

6 Critical Questions

At this time we are in the midst of carrying out the redesign of the CKM beam-line and apparatus for E921. Many preliminary studies have been undertaken. The results of these studies, thus far, have been quite encouraging. We are optimistic that we can complete this redesign to simultaneously achieve both our sensitivity and background rejections goals.

Optimism is necessary but insufficient. We enumerate here what we see as the major questions which must be convincingly answered before a serious assessment of the real feasibility of the E921 ideas can be made.

- A beam line design.

We must repeat the beam-line design and GEANT simulation, as was done for CKM, to understand in detail the beam, its tails, and the distribution and rates of the various components of beam halo including muons from upstream decays.

- Feasibility of KABES in a $230 MHz$ beam.

The results demonstrated by the Saclay group with “KABES” in NA48/2 is impressive and encouraging. The next level of technical details are not yet available. We want, and need, a deeper understanding of issues like reconstruction efficiency, rate dependences, non-Gaussian effects, etc. The input will help us fully assess how we can best combine a “KABES”-based UMS with beam vetoes, like BIVS, and the pencil beam geometry to maximize signal efficiency without allowing additional backgrounds into the sample.

- Re-evaluation of backgrounds from kaon interactions with the detector materials.

The interaction studies originally done for CKM need to be repeated for the E921 layout and kinematics.

- An estimation of backgrounds from accidentals with interactions of non-kaons in beam.

In addition to the item above we must reconsider background mechanisms like a beam pion scattering in the residual gas in the decay volume in accidental time and space coincidence with a good beam kaon. These were negligible in CKM.

- An evaluation of the sample cuts and expected backgrounds for PNN2.

We made an initial study of the backgrounds expected in the PNN2 signal region with the preliminary conclusion that the PNN2 acceptance was $1-1.4\times$ that of PNN1 with an expected background level of $20-30\%$ of the signal; $2-3\times$ worse than PNN1. We must repeat and finalize this study with the E921 layout and kinematics.

- An re-assessment of losses due to veto deadtime, reconstruction inefficiencies and other loss mechanisms.

We must re-estimate the total losses due to veto deadtimes (our trigger and DAQ are dead-timeless) and all other sources. We are presently using the CKM value for these losses (15%).

7 Plans

Our plan for advancing E921 is three fold:

1. Complete the design and background studies now underway to substantiate the case for E921 which we have outlined here.
2. Organize and execute an outside technical review of the E921 design employing a panel of world Kaon experts, as was originally done for CKM.
3. Return to Fermilab, and the PAC, with a fully vetted adaptation of the measurement technique to the E921 unseparated beam design.

8 Conclusions

Executing “*elegant world class quark flavor physics experiment*”s ought, surely, to be well within the mission of both Fermilab and our collaboration. With the adaptation of the CKM experiment to the E921 unseparated beam design we can mitigate the cost of the measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio plus a long list of other searches and measurement in both π^+ and K^+ decay by a large factor. This should address the financial concerns which have been raised.

We seek support and encouragement to advance this critical part of the Fermilab, and the world’s, experimental program. Fermilab has been a world leader in kaon physics since the inception of the lab. E921 is the vehicle to carry leadership in this area forward into the future.

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